

# Neutrino Physics in 2020

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*Abstract.* Many talks at the 16th Lomonosov Conference, dedicated to Bruno Pontecorvo, detail the remarkable progress in neutrino physics over the last two decades. In this paper, I give an opinionated, and therefore likely inaccurate, review of the future, with some opinions on how both the physics situation and future facilities will develop, focusing on the year 2020.

## 1 Introduction

There are many other papers in these proceedings describing results from past experiments, new projects and ideas for furthering our knowledge of the neutrino. There has been a great blossoming of results in the last 20 years which shed light on the properties of the neutrino, mostly based on the phenomenon of neutrino oscillation, as first described by Pontecorvo 46 years ago [1].

## 2 Notation and Semantic Issues

It is common to see the standard model particles listed from a Particle Data Group (PDG) table made in the last century. The neutrinos are listed as  $\nu_e$ ,  $\nu_\mu$  and  $\nu_\tau$ . Cabibbo mixing distinguishes the  $s$  and  $s'$  states, but the CKM matrix is mostly diagonal, so we usually use the same 6 quark labels to describe the flavor and mass eigenstates. The quarks never appear singly anyway. For neutrinos, we now know, the mass and flavor states are quite different. Which is the particle? We usually imagine a particle as being able to travel from point to point. The solution to the vacuum Schrodinger equation is a mass eigenstate, so the “particles” are  $\nu_1$ ,  $\nu_2$  and  $\nu_3$ . Since we don’t yet know the order, and families are usually separated by their mass (also the order in which we found them), the PDG chart now labels them as  $\nu_{lightest}$ ,  $\nu_{middle}$  and  $\nu_{heaviest}$ . The chart can be updated when the hierarchy is known. If we happen to be in the inverted hierarchy, the order may seem strange, and there may be reasons to rename everything. But a list of particles with the neutrino flavor states should be corrected. The hierarchy can be measured with several different techniques, so it is the focus of attention from a large fraction of the  $\nu$  community. The hierarchy is equivalent to the sign of  $\Delta m_{32}^2$ . Most physicists define  $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ . It is infrequent though possible to define  $\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$ . But if we see  $\Delta m_{12}^2$  when we think they mean  $\Delta m_{21}^2$ , it is more likely a mistake. The subscripts on the mixing angles,  $\theta_{12}$ ,  $\theta_{23}$  and  $\theta_{13}$  are just labels, and the order could have been anything. But since the  $2-\nu$  mixing approximation has been so useful, some people (wrongly) associate  $\Delta m_{12}^2$  with

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$\theta_{12}$ . Why does any of this matter? For the  $0\nu\beta\beta$  the hierarchy is crucial. But at this meeting in the talk on  $0\nu\beta\beta$  decay, a graph was shown in which  $\Delta m_{32}^2$  labels were exactly backwards. [2]

Another question is whether or not neutrino mass is “physics beyond the standard model.” While early versions of the standard model explicitly made the neutrino masses zero, since they thought that they were, it is trivial to add Dirac neutrino masses. It can be said that this would require a new discrete symmetry to prevent the appearance of Majorana mass. That is new. But the majority of theorists whom I have asked state that neutrino mass in and of itself is not beyond the standard model. They mean it is unrelated to the issues that technicolor, supersymmetry, extra dimensions, and other ideas were designed to solve.

### 3 Inside and outside the 3 $\nu$ paradigm in 2013

	value	error
$\sin^2(2\theta_{12})$	0.857	0.024
$\sin^2(2\theta_{23})$	$>0.95$	
$\sin^2(2\theta_{13})$	0.095	0.010
$\Delta m_{21}^2$	$7.5 \times 10^{-5} eV^2$	0.020
$ \Delta m_{32}^2 $	$2.32 \times 10^{-3} eV^2$	0.012

Table 1: Neutrino Mixing Parameters from 2013 PDGLive.

What do we know about neutrinos in 2013? Through the energies of a large variety of solar, atmospheric, reactor and accelerator experimenters, we now know, within the 3- $\nu$  paradigm, three mixing angles, both values of  $\Delta m^2$  and the sign of one of them. These are listed in Table 1. Many of the beautiful experiments which helped contribute to this knowledge are described in these proceedings [3]. Outside the 3- $\nu$  paradigm, these numbers may be approximations or meaningless. The currently unknown aspects of the 3- $\nu$  paradigm can be listed as follows: (A) What is the mass hierarchy or sign of  $\Delta m_{32}^2$ ? (B) Is  $\theta_{23}$  maximal and if not, which octant is it in? (C) What is the value of the CP violation parameter  $\delta_{CP}$ ? (D) What is the overall mass scale? (E) Is the nature of the neutrino Dirac or Majorana? (F) We would like to know the parameters in Table 1 more accurately.

### 4 The mass hierarchy and CP violation

There are several ways to measure the hierarchy. In accelerator experiments, matter effects provide a difference between  $\nu$  and  $\bar{\nu}$  rates which differ from those due to CP violation. Reactor experiments, which measure a different mixture

of  $\Delta m_{31}^2$  and  $\Delta m_{32}^2$  than accelerator experiments, could determine which one is larger with a large detector at 50 km with good energy resolution. JUNO and RENO50 are planning to do that. Atmospheric neutrino experiments are sensitive to matter effects through the angular distributions of  $\nu_\mu$ ,  $\bar{\nu}_\mu$  and  $\nu_e + \bar{\nu}_e$ . The PINGU collaboration's proposal for an add-on to Ice-Cube would use that signal, as would the India-Based Neutrino Observatory's magnetized ICAL detector. An observation of a supernova could provide the answer if a spectrum-swap is seen, i.e. a time dependent change in the  $\nu_\mu$  and  $\nu_e$  energy distributions due to an MSW-like effect in  $\nu\nu$  scattering. But cosmology fits could be the first to provide the answer, since the sum of neutrino masses  $\Sigma_i(m_i^\nu)$  in the normal (inverted) hierarchy is  $> 55$  ( $> 105$ )meV. In March 2013 Planck limits this sum to no more than 230 meV [4] and the error on this sum could reach 50 meV by 2019 with the measurement of B field polarization in the cosmic microwave background. This method could determine we are in the normal hierarchy, but cannot distinguish the non-hierarchical normal hierarchy from the inverted hierarchy. Keep one thing in mind about the mass hierarchy. When we measure  $\theta_{23}$ ,  $\delta_{CP}$  or the mass of the Higgs, there is value in trying to measure it better. When we measure the mass hierarchy, there is nothing to measure better. And while we often want to measure things in different ways as a consistency check on our 3- $\nu$  paradigm, I doubt that if additional physics exists in the neutrino sector, that it will manifest itself as different answers for the hierarchy.

The best way to measure CP violation will be using electron neutrino appearance in sufficiently large long-baseline accelerator experiments. NO $\nu$ A and T2K will make the next measurements in this decade until larger experiments are built in the next. Long distances aren't required, but such future experiments will be put at a long enough baseline to assure resolution of the mass hierarchy. The candidate programs are LBNE in the U.S. (favored by the recent "Snowmass" meeting of the HEP community), Hyper-K in Japan, and LBNO in Europe. From a funding/politics point of view, the latter program seems unlikely. Each program has been described at this conference [5–7]. These are sufficiently long-term beam and detector construction projects that it will be beyond 2020 before any exist and have results.

## 5 The Challenge of neutrinoless double beta decay ( $0\nu\beta\beta$ )

If the neutrino is Majorana,  $0\nu\beta\beta$  decay happens at predictable rates depending on masses, mixing angles and matrix elements. If the neutrino is Dirac, it does not happen. Matrix element calculations are difficult, but the differences between calculations are at most a factor of four. Experiments will soon be testing rates at a level that will soon be sensitive to part of the available parameter space for the inverted hierarchy, but since sensitivity improves only

with the fourth root of statistics, covering that entire parameter space will take some time. Sensitivity to the hierarchical normal hierarchy is in the distant future. In that difficult case, we can contrast the sensitivity of  $0\nu\beta\beta$ , which is sensitive to  $\Sigma_i U_{ei}^2 m_i$  to tritium beta decay sensitive to  $\Sigma_i U_{ei}^2 m_i^2$ . We now know the central value of everything but  $m_1$ , but since  $m_2 > m_1$  we can calculate both sums. In this interesting case,  $0\nu\beta\beta$  decay is dominated by  $m_2$ , and tritium beta decay is dominated by  $m_3$ .

## 6 Predictions and prognosis for 2020

Where will the neutrino world be in the year 2020? I think we will have measured the hierarchy. If  $\theta_{23}$  isn't too close to  $\pi/4$ , we will know its quadrant. The errors listed for the parameters in Table 1 will be smaller. We'll have more information on  $\delta_{CP}$ , but unless we are quite lucky, we won't have satisfactorily established CP violation. And we won't yet know whether the neutrino is Dirac or Majorana.

I suspect we actually will know something about the overall mass scale, from cosmology experiments as mentioned in Section 4. Those searches involve fits of cosmological parameters, including neutrino mass. Since those fits are model dependent, there may be effects outside the currently favored  $\Lambda$ CDM model which mimic neutrino mass. The challenge for the particle physics community will be to evaluate the fits and their assumptions and decide whether to accept them, since they are based in part on issues beyond our expertise. But as the solar neutrino problem taught us, it would be a mistake to discount answers that come from fields we don't totally understand.

The remaining program in 2020 will be to measure  $\delta_{CP}$  to determine whether there is CP violation. We'll be able to determine the Dirac/Majorana nature of the neutrino in a short time if the hierarchy is inverted, but in a much longer time frame for the normal hierarchy. Will it be important to improve measurements of the parameters in Table I? The answer depends on the state of neutrino theory at the time. If theorists can find any possible sense in these values, then more accurate measurements might be needed. If the theoretical situation on masses and mixing angles hasn't changed, then extraordinary efforts to measure neutrino parameters better don't seem justified to me. The exceptions are if  $\theta_{13}$  is still  $\pi/2$  within errors or  $\delta_{CP}$  is indistinguishable from 0 or  $\pi$ .

I've been assuming the validity of the  $3\nu$  paradigm. Some "anomalies" have stimulated interest in new experiments to search for sterile neutrinos with an eV scale mass. This reminds us that there is always the possibility that these or other experiments will find something in the neutrino sector beyond our current understanding of  $3\nu$  mixing. That would point us toward new experiments. I don't know what those new experiments would be.

## 7 Neutrino miracles

The conference participants had a tour of Sergeiv Prosad/Zagorsk. Several miracles were described to us there. One definition of a miracle could be whenever we have a failure of Murphy's Law [8]. A collection of observations about the seeming "intelligent design" of neutrino properties from about ten years ago is worth recounting [9]: 1) *The optimum choice for  $\Delta m_{21}^2$ ? – Such as to give resonant transition (MSW effect) in the middle of solar energy spectrum;* 2) *The optimum choice for  $\theta_{12}$ ? – Big enough for oscillations to be seen in KamLAND;* 3) *The optimum choice for  $\Delta m_{32}^2$ ? – Such as to give full oscillation in the middle of the range of possible distances that atmospheric  $\nu$ s travel to get to the detector;* 4) *The optimum choice for  $\theta_{23}$ ? – Big enough so that oscillations could be seen easily;* 5) *The optimum choice for  $\theta_{13}$ ? – Small enough so as not to confuse interpretation of the above; But the acid test is will  $\theta_{13}$  be big enough to see CP violation and determine the hierarchy?* The last condition has been famously met [10]. Let me extrapolate to the miracles we might add to this list by 2020. At the risk of being too greedy, we would like to see our program move forward, and that will happen best with: 1)  $\delta_{CP} \sim \pi/2$  to most quickly determine the hierarchy and to get large CP violation; 2) The inverted hierarchy, so we can tell Dirac/Majorana and maybe the beta decay endpoint; 3) Majorana, which seems to be more interesting to theorists, and we want our theorists to be happy.

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